

Resolving Picosecond Carrier Dynamics at the Nanoscale – The Attolight Allalin Chronos TRCL Solution

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Abstract

Many critical processes happen before nanoseconds even start. In the picosecond to nanosecond timescale, luminescence experiments capture fast relaxation and initial recombination dynamics: formation and fast decay of excitons, fast energy transfer, and vibrational relaxation. This time domain is frequently used to study dominant recombination pathways in semiconductors, providing key metrics for assessing material quality and device performance — insights that are critical for advanced materials research, next-generation transistors, high-efficiency LEDs, emerging AI hardware, and other cutting-edge semiconductor technologies.

Overcoming the Sub-10 ps Measurement Challenge

GaN, one of the most well-known wide-bandgap semiconductors, exhibits ultrafast initial exciton formation and relaxation dynamics in the sub-picosecond range. However, the luminescence rise time for time-resolved photoluminescence (TRPL) in high-quality pure GaN is often reported in the range of 10-100 ps, limited by the instrument response function. In fact, measuring sub-10 ps rise times is technically very challenging: it requires a pulsed excitation source and detector with minimal jitter, as well as high signal-to-noise ratio to capture the fastest dynamics. With our time-resolved cathodoluminescence (TRCL) system using an ultrafast pulsed laser (pulse duration ~3 ps) and a ps-resolution streak camera, we can reliably measure rise times below 10 ps (Figure 1), which clearly demonstrates the high temporal resolution of the entire TRCL system and provides the precision needed to resolve most ps-scale carrier dynamics in luminescence experiments.

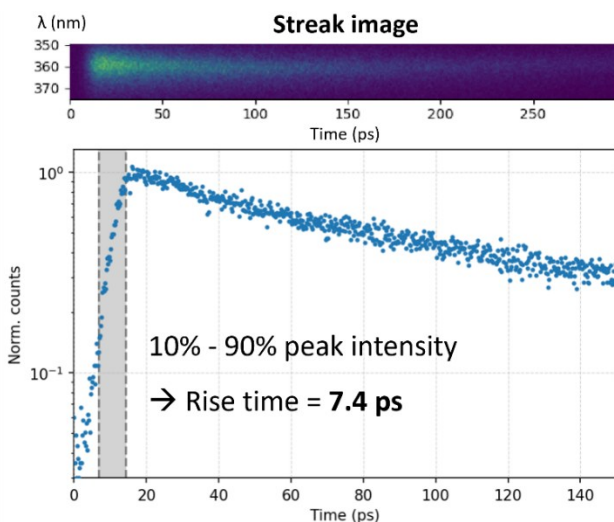


Figure 1: Streak image of GaN under 5 keV pulsed electron-beam (e-beam) excitation. The spectrally integrated TRCL decay exhibits a 10–90% rise time of ~7.4 ps, demonstrating the picosecond temporal resolution of our system.

Preserving Nanoscale Spatial Resolution (< 15 nm)

While exploring physics at the picosecond timescale with high temporal resolution, we preserve nanoscale spatial resolution even in pulsed mode, achieving <15 nm resolution with a laser-pulsed electron beam (Figure 2). This maintains the key advantage of CL over PL: excitation beyond the diffraction limit. With such high spatial resolution, nanoscale structural features observed in scanning electron microscopy (SEM) can be directly correlated with TRCL through hyperspectral imaging, providing rich and comprehensive information in a single experiment.

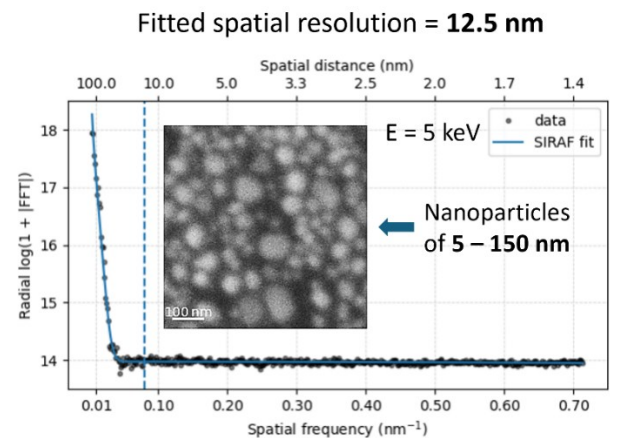


Figure 2: SIRAF [1] analysis of the SEM image of gold nanoparticles under 5 keV pulsed e-beam excitation. The analysis indicates a spatial resolution of ~12.5 nm, demonstrating the nanoscale accuracy of our pulsed SEM.

Ease of Use and Actionable Data Extraction

With such rich and high-dimensional information contained in a single hyperspectral dataset, a key practical question is how to efficiently extract the most relevant insights. To address this, our company provides dedicated support through a professional applications team, including skilled Python developers (contributors to the well-known HyperSpy package [2]), experienced experimentalists with over 15 years

of expertise across all TRCL configurations—including beam blanker [3], laser-pulsed excitation [4], time-correlated single photon counting (TCSPC) [5], second-order intensity correlation function (g^2) measurements [6], pump-probe CL spectroscopy [7] and various streak camera systems [8]—and material scientists with strong backgrounds in both TRPL and TRCL on emerging semiconductor systems.

In addition, our user community has developed and shared a variety of advanced data processing approaches, enabling rapid extraction of key information—such as carrier lifetime maps (Figure 3), dopant concentration maps [9], and defect-related signatures (Figure 3) [10, 11]—within seconds to minutes. Based on your specific requirements, we further develop tailored analysis workflows to accelerate your data processing and unlock the full potential of TRCL measurements.

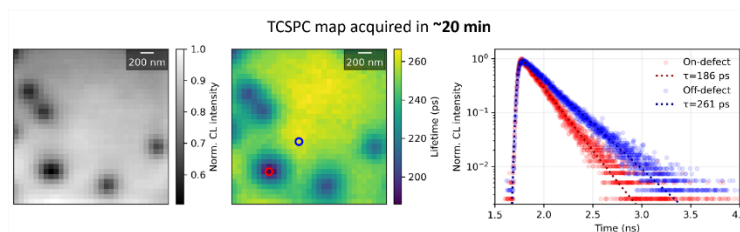


Figure 3: TCSPC mapping of GaN CL under 5 keV pulsed e-beam excitation.

Left: Time-integrated CL map, where embedded defects appear as dark spots. Middle: Carrier lifetime map generated using an advanced Python analysis pipeline developed by our Application Engineer, Nicolas Tappy [9], revealing the impact of embedded defects on the local carrier dynamics. Right: TRCL decays extracted from two locations in the lifetime map: on a defect (red) and away from a defect (blue). The fitted decay curves reveal ps-scale carrier lifetimes and clearly demonstrate the influence of defects on the recombination dynamics. The complete TCSPC map was acquired in ~ 20 minutes. Given the excellent signal-to-noise ratio achieved, the acquisition time can be further reduced, while the current measurement already demonstrates the excellent stability of the system under pulsed e-beam operation.

References:

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